

Observations of Insect Damage to Leaves of Woodland Eucalypts on the Central Western Slopes of New South Wales: 1990 to 2004

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Damage to leaves of ~680 eucalypt trees at 17 paired sites, distributed across three soil landscapes near Molong and Manildra (NSW), was monitored each autumn from 1990 to 2004. Insect damage was assessed by estimating the proportion of damaged leaves on each tree. Across all species and sites, and for most of the time, mean damage fluctuated between 10 and 25 % of leaves obviously damaged. Higher values (>30 % of leaves damaged) were recorded in 1990 and 1994, which coincided with increased abundance of Scarabeidae. After c.1995 abundance of Scarabeidae declined and most leaf damage was due to feeding by other insects. Relative damage levels to individual species changed over time and for *Eucalyptus albens* and *E. melliodora* was associated with the soil landscape in which the trees occurred. When Scarabeidae were active, *E. albens* and/or *E. blakelyi-dealbata* showed higher leaf damage than *E. bridgesiana*, *E. microcarpa* and *E. melliodora* although the last mentioned was damaged by insects other than Scarabeidae during this period. Leaf damage across all trees and times was negatively correlated with warm season rainfall 4 years previously. Contrary to expectations, most individual trees did not experience severe leaf damage in consecutive years.

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INTRODUCTION

During the summer of 1989-90, eucalypts in the Central West of NSW experienced a severe attack by Christmas beetles (*Anoploganthus* spp., Scarabeidae). It was reported (Dick 1990a) to be the worst attack since the 1970s. They were also seen as a threat to on-farm tree plantings, which were increasing in that area at the time. A newspaper article (Anon. 1990, p. 25) cited a CSIRO entomologist as saying that *Eucalyptus blakelyi* was no longer a suitable tree for on-farm planting and as waterlogging was a major factor in eucalypt dieback, "...there may be a case for not planting native trees in heavily stressed waterlogged sites, where it may be better to plant exotics like willows." In another article, Dick (1990b) reported that CSIRO researchers had found 'insect-resistant

trees', which they intended to clone for potential use in on-farm tree plantings.

[This project was terminated in the mid 1990s but not before the proportion of cineole in leaf terpenoids was identified as a major factor in explaining differing resistances to beetle defoliation (Edwards et al. 1990, 1993). Cloning was apparently not achieved prior to cessation of funding though orchards produced from seed of resistant trees were established (Floyd and Farrow 1995)].

As defoliation by Scarabeidae was a major contributor to dieback (a symptom of a disorder with various causes, including insect attack) on the Northern Tablelands in the 1970s (Nadolny 1995), the beetle attack of 1989-90 appeared to be a portent of worse to come in the Central West. One of us [WS], a newly-appointed 'investigations officer', was asked:

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(a) was this event going to be repeated on a regular basis as occurred in the Northern Tablelands and (b) was it true that the same trees were attacked year after year? Though not providing specific answers to these questions, a considerable volume of work on insect defoliation and eucalypt dieback in general was being reported at the time. Landsberg et al. (1990), for example, proposed five possible explanations for chronic defoliation by insects:

1. It is a naturally-recurring phenomenon. For example, Curtis' (1989) review of dieback on the Northern Tablelands of NSW noted that it had occurred several times in the previous 100 years and that wet summers were associated with greater insect abundance. After an extensive review of dieback events in Australia and overseas, White (1986) proposed that recurrent dieback events were due to changes in weather patterns. Where rainfall patterns resulted in moisture stress, subsequent changes in eucalypt physiology made them more attractive to insects and/or pathogens.
2. 'Stressed trees' – trees stressed, e.g. by soil degradation or waterlogging, have reduced ability to recover from insect attack.
3. 'Ecosystem imbalance' – some insects have been favoured by tree clearing and pasture improvement resulting in increased abundance on the remaining trees.
4. 'Release from natural enemies' – abundance of predators, including other insects and birds, has declined due to reduced habitat resources in degraded tree remnants.
5. 'Nutrient (nitrogen) enrichment' – increased soil fertility due to pasture improvement has increased the nutrient quality of tree leaves and hence their attractiveness to insects.
6. 'Maladapted trees' – Edwards et al. (1993) and Floyd and Farrow (1995) subsequently suggested that reduced opportunities for eucalypt reproduction in agricultural landscapes had not allowed types resistant to insect attack to fully develop.

From an investigation of soil factors, tree health, insect abundance and herbivory in paired stands of intact and degraded stands of *Eucalyptus blakelyi* – *E. melliodora* woodland, Landsberg et al. (1990) concluded that explanation #5 was the most likely reason for enhanced abundance of insects on trees and suggested that the accumulation of nitrogen in stock camps around tree stands was implicated. The other explanations were not entirely ruled out and, as noted

by Wylie and Landsberg (1990), any one or more may have application in a particular situation.

It was also clear that some eucalypt species were more likely to be defoliated than others. Curtis (1989) reported that *E. nova-anglica*, *E. blakelyi* and *E. melliodora* were more severely affected than *E. pauciflora* on the Northern Tablelands of NSW. However, relative damage between species appeared to vary regionally. Fox and Morrow (1983) reported that *E. pauciflora* and *E. blakelyi* were both heavily damaged in southern NSW and that *E. pauciflora* suffered greater levels of damage when trees were growing in mixed rather than monospecific stands. Wylie and Landsberg (1990) noted that dieback affected trees of all ages but was more severe in older-age classes than younger ones. It was also evident that insect damage levels varied between individuals of the same species in the same area and even between different parts of the one tree (e.g. Lowman and Heatwole 1992, Edwards et al. 1993).

Thus despite a decade or so of research into eucalypt dieback and defoliation, the causative factors were far from clear in autumn 1990 when the eucalypt monitoring project described below commenced. It was designed to answer the two questions posed earlier and at the same time test some of the then current explanations for chronic defoliation. Its primary aim was to monitor damage by Scarabeidae, which was seen as the major threat at the time. The aims of the project were to:

- document fluctuations in the extent of leaf damage to a large number of eucalypts over a period of time;
- examine a subset of the above (tagged trees) for evidence of consistent differences in the level of leaf damage to individual trees over time;
- investigate whether damage was associated with environmental factors such as those suggested by Landsberg et al. (1990) above.

METHODS

Site selection and description

It was considered that about ten sites in each of three main agricultural landscapes (Kovac et al.'s (1990) 'Manildra', 'Canowindra' and 'Black Rock' soil landscapes; Table 1) in the Manildra–Molong area would be sufficient for the survey. In early 1990, readily-locatable (e.g. road junctions, railway crossings) groups of trees extending from road reserves into adjacent paddocks were marked on aerial photographs of the Molong 1:50 000 topographic

Table 1. Brief descriptions of the three Central Western NSW soil landscapes sampled (Kovac et al. 1990, B.W. Murphy pers. comm.).

Soil Landscape	Lithology	Soils	Topography	Main land use
Black Rock (Br)	Sandstone, conglomerate, shale	Red podzolics on upper to midslopes. Yellow podzolics in drainage lines. Low to moderate fertility	Rolling low hills. Relief 60-80 m. Slopes 8-20%	Grazing – often of native pastures.
Canowindra (Cd)	Porphyry, shale, limestone	Non-calcic brown soils with some red podzolics or red earths on upper-midslopes. Yellow and brown solodics in some drainage lines. Moderate to high fertility.	Undulating low hills. Relief 20-60 m. Slopes 2-8%	Broadacre crops and pastures in rotation.
Manildra (Mn)	Shale, porphyry, limestone	Non-calcic brown soils on mid to upper slopes. Red and brown podzolics with some red earths and euchrozems on higher slopes. Red brown earths on lower slopes. Yellow and red solodics in drainage lines. Moderate to high fertility but tending to be more ‘patchy’ than Canowindra.	Undulating to rolling low hills. Relief 20-80 m. Slopes 6-16%.	Broadacre crops and pastures in rotation.

map. Each pre-selected site was then assessed in the field for satisfying the following criteria: (a) presence of at least 20 naturally-occurring eucalypts along the roadside and 20 in the adjacent paddock, (b) not near buildings where tree plantings may have occurred, and (c) where possible, not in drainage lines (which represented a different environment to most of the country being surveyed). If a site was unsuitable, and most were due to insufficient trees being present, the surveyor proceeded to the next site.

Ultimately six pairs of sites in each landscape were selected but one in the Black Rock landscape was subsequently abandoned due to difficulty in distinguishing two closely-related species. The locations of the remaining paired sites, Black Rock (Br) 1, 3, 4, 5 and 6, Canowindra (Cd) 1–6 and Manildra (Mn) 1–6 are shown in Fig. 1. Apart from Br3 (Fig. 2) and Br4, none of the stands was near-intact and all had been thinned to varying extents. As roads were often located in transition areas between two vegetation communities, and often at lower elevations than upslope paddocks, species composition of the roadside community did not always match that of the adjacent paddock, e.g. Br6, Cd6, Mn1, 2 and 3 (Table 2). Sizes of sites ranged from up to ~300 m of roadside to ~1 hectare of paddock. In addition to soil landscape

and location (roadside or paddock), the composition of the groundstorey (native v. exotic grass dominant) was also recorded at each site.

Trees were identified using local tree identification guides but many specimens were submitted to the Royal Botanic Gardens, Sydney, for confirmation. Red gums presented particular difficulty in the Molong–Manildra environment. Both *E. blakelyi* and *E. dealbata* were present but intergrades, sometimes identified as ‘*E. blakelyi* ssp. *irrorata*’, were particularly common. For this reason, all the red gums encountered in the survey have been treated together as ‘*E. blakelyi-dealbata*’.

Assessment of insect damage

Assessments of the ‘dieback condition’ of entire trees, e.g. as described by Landsberg (1989), are more likely to reflect past rather than current levels of defoliation and hence were of limited use for annual monitoring as proposed here. Many assessments of defoliation have been based on time-consuming measurements of the volume of foliage that has been removed from a tree. Visual estimates of the proportion of leaf loss are more rapid and, as reported by Landsberg (1989), can be estimated

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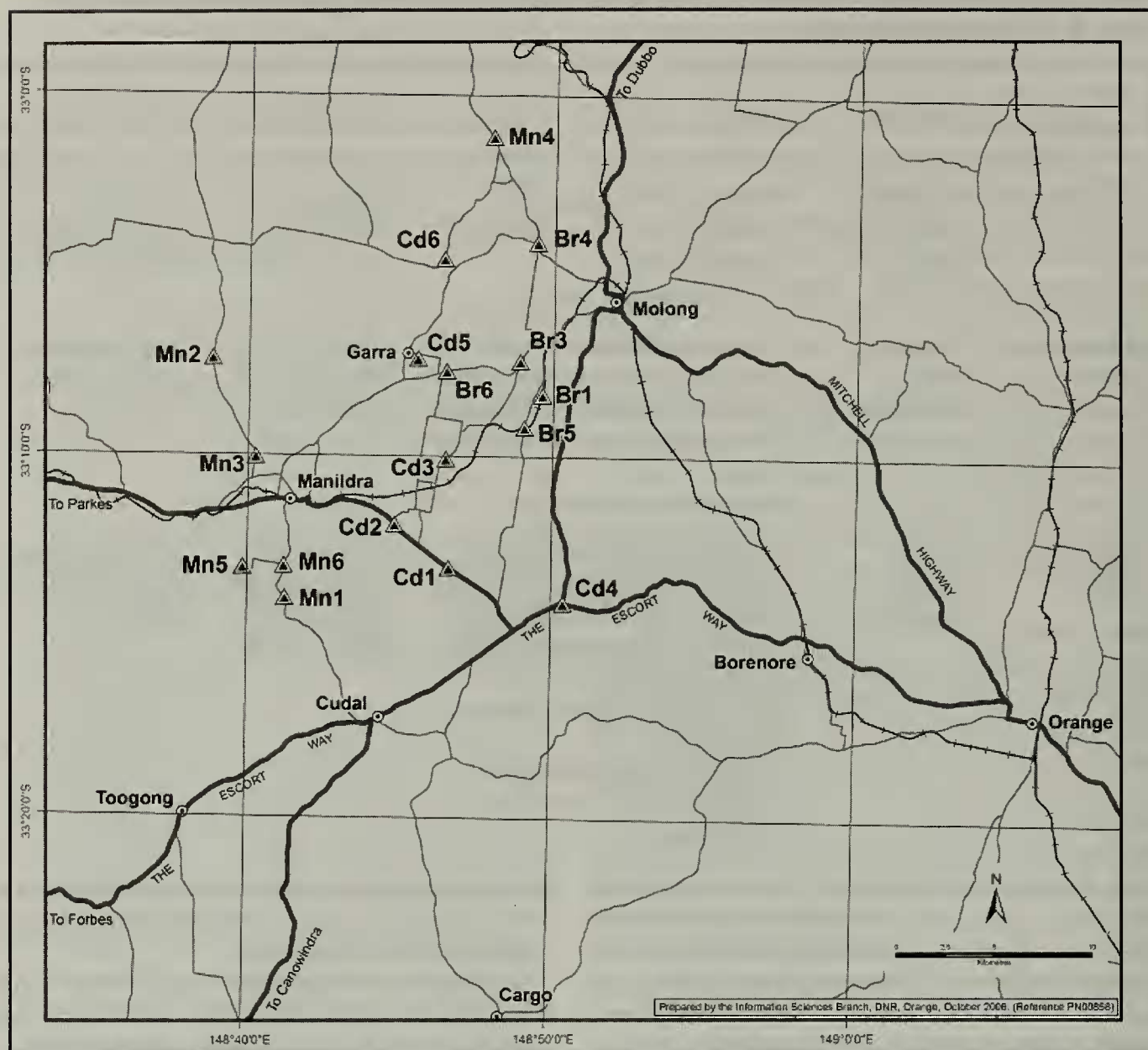


Figure 1. Location of the 17 paired eucalypt monitoring sites (Δ) in the Molong–Manildra area of Central Western NSW.

(though often over-estimated) in a consistent manner by a single observer but may vary between observers. For the purposes of this survey, damage assessment needed to be rapid and consistent, especially from year to year, though not necessarily an absolute measure of damage. Instead, an assessment of the proportion of damaged leaves on each tree was undertaken. This involved examining a clump of leaves on a tree and estimating the proportion that showed obvious damage, i.e. could be easily seen with the unaided eye or with binoculars. This was repeated for a number of clumps and the results averaged. Hence, a rating of 10 % meant that, on average, 10 % of the leaves on that tree had obvious damage. ‘Damage’ included removal of sections of leaf (either holes or along the margins),

presence of galls, ‘skeletonisation’ and other forms of leaf stress. Removal of entire leaves could not be estimated. In the first season (summer of 1989–90), a three point scale was employed: ‘nil/minor’ damage (≤ 10 % of leaves were damaged), ‘moderate’ (>10 –50 %), ‘severe’ (>50 %). In subsequent years, the proportion of damaged leaves was estimated to the nearest 10%.

The procedure did not, therefore, distinguish damage by Scarabeidae, which produce characteristic sawtooth-like edges on leaves, from other forms of insect damage; though whether damage was primarily due to beetles was noted on field sheets. Another consequence of this procedure was that removal of a large part of an individual leaf was considered the



Figure 2. A relatively intact grassy *E. albens* woodland in a paddock at site Br3 during autumn 2000. This site has since been further degraded by tree removal and the planting of exotic trees.

same as removal of a small part.

It was also assumed that leaves being assessed were different from those assessed the previous year, i.e. that leaves were <1 year old. Although reports of individual eucalypt leaves surviving for up to 3 years exist (e.g. Lowman and Heatwole 1992), Jacobs (1955) reported the average leaf-life of forest trees at about 1.5 years, dependent on factors such as position in the canopy, growth rate, wind changes and insect attack. Jacobs noted that bursts of growth such as occur after insect attack are associated with increased leaf-fall such that the average life of remaining leaves is <1 year. Bursts of growth that commonly occur on woodland eucalypts in autumn and spring may also be associated with increased leaf fall; and even if some leaves live for >1 year, these flushes ensure that many are <1 year old.

Site monitoring

Commencing in April 1990, the first 20 trees, regardless of size, encountered along the roadside at each site were assessed for insect damage. Species and the main leaf type (adult, juvenile) were also noted for each tree. This was repeated in the adjacent paddock. The sites were reassessed each year – ideally in March when Scarabeidae activity had ceased and

before new autumn leaves were obvious – until 2004. Trees were assessed by the same observer [WS] on all occasions. Between 1991 and 1993, trees at five of the sites (Table 2) were tagged so that damage to individual trees could be monitored. When tree deaths occurred or a tree could not be relocated, additional trees were tagged to maintain the number of trees monitored at 20.

The same groups of untagged trees were assessed each year but this did not necessarily involve exactly the same trees in each group. In most cases this was due to tree deaths (natural and deliberate) and excessive browsing by stock but in one case by the incorporation of roadside trees into the adjacent paddock by new fencing. These changes necessitated the assessment of new trees, which were sometimes at a considerable distance from the original site. Sites Mn1 (roadside) and Mn2 (paddock) were abandoned in 2001 due to insufficient numbers of trees being present within reasonable walking distance. Monitoring of paddock trees was progressively scaled back from 2001 (when only tagged trees were monitored) to 2003 when only roadside trees were monitored.

Table 2. Brief descriptions of eucalypt sites monitored from 1990 to 2004

ROADSIDE TREES										PADDOCK TREES									
Site no.	Ground-storey	alb	mell	iror	brid	mier	poly	(juv)	Ground-storey	alb	mell	iror	brid	mier	poly	(juv)			
Br1 *	exotic	30	0	70	0	0	0	25	exotic	11	0	89	0	0	0	0			
Br3 *	native	66	0	34	0	0	0	22	native	82	0	19	0	0	0	21			
Br4	exotic	100	0	0	0	0	0	52	native	92	0	8	0	0	0	44			
Br5	exotic	27	44	30	0	0	0	29	exotic	7	79	14	0	0	0	2			
Br6	exotic	0	51	49	0	0	0	16	native	0	0	100	0	0	0	49			
Mean#		44	19	37	0	0	0	29		39	15	46	0	0	0	22			
Cd1	native	100	0	0	0	0	0	58	exotic	100	0	0	0	0	0	0			
Cd2	native	100	0	0	0	0	0	64	exotic	100	0	0	0	0	0	17			
Cd3	native	100	0	0	0	0	0	4	exotic	100	0	0	0	0	0	0			
Cd4	exotic	95	5	0	0	0	0	26	exotic	100	0	0	0	0	0	1			
Cd5	exotic	1	83	16	0	0	0	2	exotic	0	95	6	0	0	0	0			
Cd6 *	exotic	0	50	0	50	0	0	20	native	25	5	70	0	0	0	0			
Mean		66	23	3	8	0	0	29		69	17	15	0	0	0	3			
Mn1	exotic	51	45	0	0	4	0	75	exotic	63	1	0	0	0	37	9			
Mn2 *	native	80	1	0	0	7	13	17	exotic	5	0	95	0	0	0	28			
Mn3	exotic	0	27	73	0	0	0	21	exotic	0	89	1	10	0	0	1			
Mn4 *	exotic	0	79	16	5	0	0	16	exotic	0	80	5	15	0	0	0			
Mn5	native	65	35	0	0	0	0	25	native	56	44	0	0	0	0	5			
Mn6	native	0	0	0	0	100	0	0	native	0	0	0	0	100	0	1			
Mean		32	31	15	1	19	2	24		20	38	15	5	23	0	7			

#Means based on actual tree numbers over all observations and rounded to nearest integer

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Data analysis

Over the 15 years of observation, 680 individual trees were examined, yielding 8804 assessments of leaf damage. Statistical analysis of this large data set was complicated by the highly structured and confounded nature of the classifying factors of: soil landscape (Canowindra, Black Rock, Manildra), location (paddock, roadside), pasture type (exotic, native), species (*E. albens*, *E. microcarpa*, *E. melliodora*, *E. bridgesiana*, *E. blakelyi-dealbata*), leaf type (adult, juvenile) and time (1990, 1991 ... 2004). For example, *E. microcarpa* was only found on the Manildra soil landscape and primarily on sites with a native pasture understorey. Confounding of this degree could result in the misinterpretation of the cause of an apparent statistically significant outcome. To minimise the chance of misinterpretation, a number of separate linear mixed model analyses were run. Initially all data were used to quantify the extent of leaf damage over the full period of observation, with focus only given to the main order effect of time. Three further analyses were performed on subsetting data formed by selecting the major species, viz. *E. albens*, *E. melliodora* and *E. blakelyi-dealbata*, with 4033, 2106 and 1808 records respectively. Where estimable, only main-order (e.g. soil landscape, time) and interactions up to first order (e.g. soil landscape by time) were included in these models.

The response variable for the analyses, viz. proportion of leaves damaged on each tree, covered the full range of 0 to 100%. Therefore to statistically model the proportion, p , of severely damaged leaves on a tree as a function of the above explanatory factors, a logistic transformation (Cunningham et al. 2005) was applied within a generalised linear mixed model framework using GenStat (2005). Significance of interaction terms was tested by examining Wald statistics formed by dropping, in turn, these individual terms from the full fixed model. High degree splines were fitted to these estimated means to indicate general temporal trends.

Correlation coefficients were derived between the estimated proportion of leaves damaged per tree from the analysis of all data and various measures of moisture status. One measure examined actual rainfall in the form of either total annual, warm season (September to February) or cool season (March to August) rainfall lagged from the time of observation by 1, 2, 3 or 4 years. Another measure re-expressed each of these measures of rainfall as a standardised index by creating a running mean of the three most recent rainfall records, subtracting three times the long term average and then dividing by the long term average. This standardisation is similar to that used by Foley (1957) and is referred to here as 'three-year

Foley's index'.

To investigate the incidence of severe leaf damage (defined as a tree having $\geq 40\%$ of leaves damaged) in consecutive years, a contingency table was formed from the annual damage levels of the 206 individually tagged trees. For trees that were continuously monitored from 1991–93 to 2004, there were 13–11 opportunities of severe leaf damage in consecutive years.

RESULTS

Rainfall (Fig. 3a) during the 14 years of monitoring varied considerably with occasional wet years (e.g. 1992) and droughts (e.g. 1994–1995, 1997, 2002). The three-year Foley's index (which provides some indication of cumulative soil moisture over the relevant period) for annual rainfall, peaked in 1992 reflecting a run of average to above-average seasons but dipped in 1995 and 2003 reflecting runs of below-average rainfall. A similar pattern was evident for cool season rainfall (Fig. 3b) but not for warm season rainfall where indices for the periods 1986–90 and 2002–03 were negative, and those for 1992–98 were positive (Fig. 3c).

In Fig. 4b, it is evident that overall insect damage was moderate when assessed in most autumns with $\sim 20\%$ of leaves on the 'average tree' damaged. Significantly higher average damage levels of 33 % and 37 % were evident in 1990 and 1994 respectively. When damage to the three most common species, *E. albens*, *E. melliodora* and *E. blakelyi-dealbata*, was examined (Figs. 4c, d, e), time (year of observation) was again the main significant explanatory variable except for *E. albens* and *E. melliodora*, where soil landscape interacted with time.

Much of the damage up to about 1995 was due to Scarabeidae. Maximum leaf damage was recorded in 1990, an acknowledged 'bad beetle year' (Dick 1990a), and again in 1994, though at this time damage by other insects was also evident. Differences in damage levels between tree species were suspected across the period of observation but the statistical significance was not determined due to the potential confounding of effects. Nevertheless, when Scarabeidae were the most obvious reason for damage, average damage to species appeared to decrease in the following order: *E. albens* or *E. blakeleyi-dealbata*, *E. bridgesiana*, *E. microcarpa* and *E. melliodora*. *Eucalyptus melliodora* was severely damaged in 1993–95 but leaf damage ('withered and dehydrated') was consistent with the occurrence of non-lerp-forming Psyllidae, rather than Scarabeidae. From 1995 onwards, species ranking with respect to damage changed, though *E. albens*

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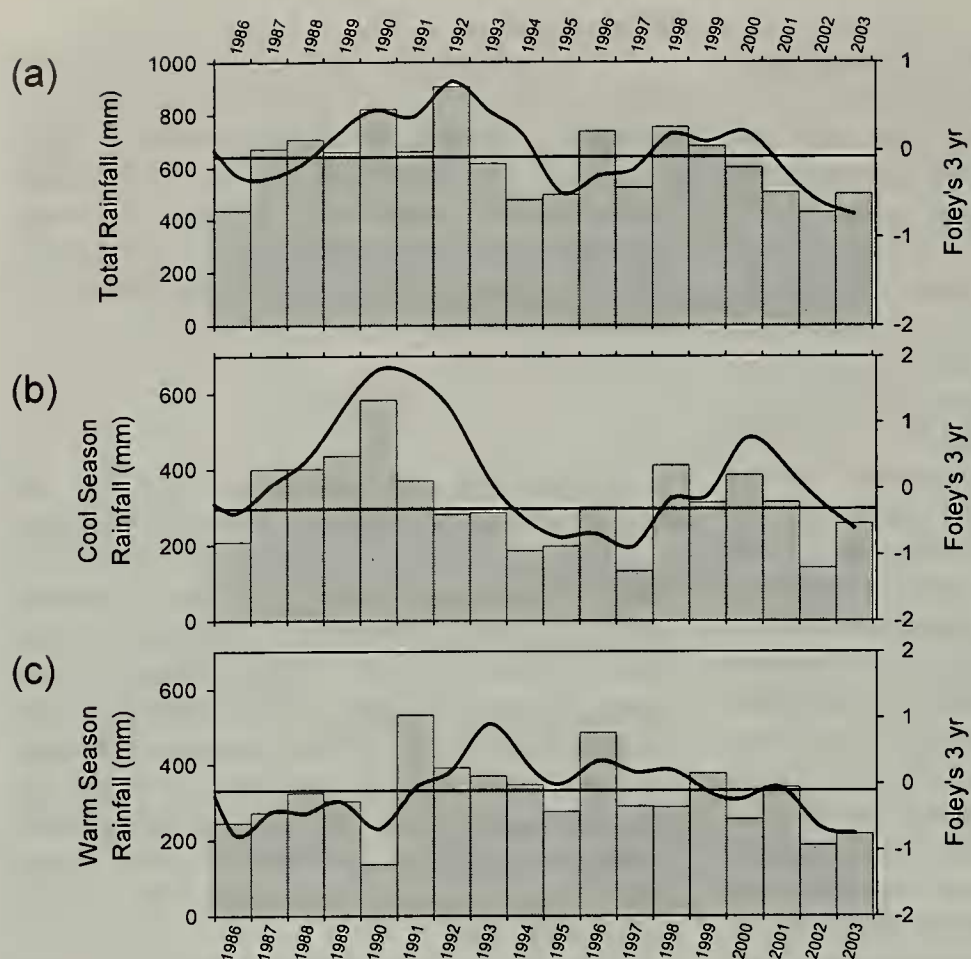


Figure 3. (a) Annual, (b) Cool season (March to August) and (c) Warm season (September to February) rainfall at Manildra P.O. in the years immediately prior to and during the insect damage survey. Long term (1960–90) averages shown by horizontal lines and three-year Foley’s indices by undulating lines.

generally showed the most damage.

Apart from time of observation, very few of the potential explanatory variables were statistically significant in explaining leaf damage. Past rainfall, however, correlated significantly with leaf damage. Across all years of observation, highest correlations were with Foley’s three-year moisture index of 4 years previous. There was a negative correlation with the warm season index and a lower but positive correlation with the cool season index (Table 3). The relationship can be seen by comparing Fig. 4b (annual leaf damage) with Fig. 4a, where the indices have been staggered by 4 years. A deficit in warm season rainfall was associated with higher leaf damage (at least in 2 of the 15 years) and an increase by reduced levels of damage 4 years later. An opposite trend was evident for cool season rainfall.

However, during the period 1996–2004 (when Scarabeidae were not particularly active), leaf damage correlated negatively with the calendar year rainfall ($r = -0.86$) and to a lesser extent, warm season rainfall (r

$= -0.66$) immediately prior to the time of observation.

Repeated observations of the same (206 tagged) trees indicated that 24 % (49) of the trees never experienced severe leaf damage by insects; a further 37 % (76 trees) experienced severe leaf damage on up to three occasions but not in consecutive years. Most trees (61 %), therefore, were not subjected to severe leaf damage in consecutive years. One tree, however, experienced ten severe attacks over 14 years, eight of which were in consecutive years. Between these two extremes, there were low numbers of trees that experienced severe leaf damage in consecutive years (Fig. 5).

DISCUSSION

As it turned out, the severe defoliation caused by Scarabeidae in 1989–90 was not a precursor of

widespread dieback in the Molong–Manildra area of Central Western NSW. Nevertheless the number of trees that died during the 15 years of survey was surprising. In some cases, the cause was obvious (e.g. deliberate removal associated with roadworks), suggestive (e.g. severe browsing of saplings by domestic stock or mature trees with a heavy mistletoe burden) or not evident (e.g. rapid death of mature *E. melliodora*) but, apart from the few cases of the latter, it could not be described as ‘dieback’ (rapid and widespread death; Nadolny 1995). However, further south in the Boorowa–Young–Harden area, dieback has been evident for many years and, for *E. blakelyi* at least, appears to be associated with severe damage by Psyllidae.

Damage by Scarabeidae was evident every summer, particularly in 1989–90 and 1993–94, but their role in overall damage declined after about 1994 and thereafter appeared to be confined mainly to *E. albens* and *E. blakelyi-dealbata*. Reference

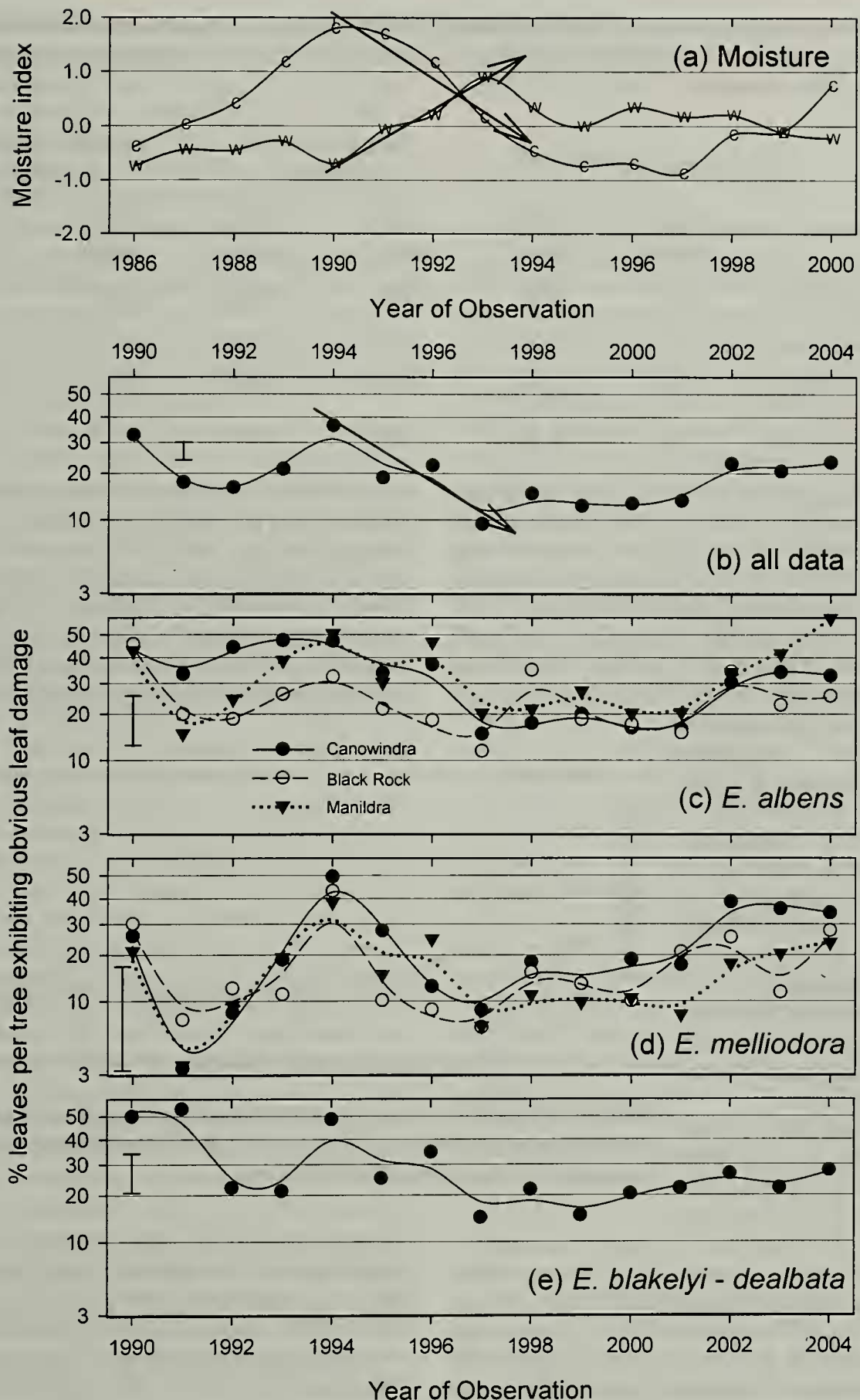


Figure 4. (a) Three-year Foley's rainfall indices for cool season (C) and warm season (W) rainfall four years prior to the average damage levels recorded for (b) all eucalypt trees, (c) *E. albens* trees, (d) *E. melliodora* trees and (e) *E. blakelyi-dealbata* trees when assessed each autumn from 1990 to 2004. Damage is expressed as the estimated percentage of leaves with obvious insect damage on each tree and graphed on the logit scale.

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Table 3. Correlations between average leaf damage (%) and previous (1 to 4 years) rainfall totals (calendar year, warm season (September to February), cool season (March to August) and corresponding three-year Foley's indices.

	CALANDER YEAR		COOL SEASON (6 months)		WARM SEASON (6 Months)	
	Total rainfall	Foley's Index	Total rainfall	Foley's Index	Total rainfall	Foley's Index
4 years previously	0.26	0.28	0.52	0.51	−0.50	−0.76
3 years previously	0.20	0.19	0.43	0.57	0.15	−0.35
2 years previously	0.25	0.39	0.10	0.47	0.13	−0.15
1 year previously	−0.24	0.09	−0.06	0.20	−0.20	0.05

to Fig. 4 suggests that there was a low background level of damage (i.e. ~20 % of leaves with obvious damage), which was exceeded in occasional years when Scarabeidae (or possibly Psyllidae in the case of *E. melliodora* around 1993–95) were active. These results are consistent with the long-term observations of Pook et al. (1998) in an *E. maculata* forest on the south coast of NSW. No surveys were carried out in 2005 and 2006 but incidental observations suggested no major change in levels of either leaf damage or abundance of Scarabeidae. This was corroborated by a Molong landholder, who observed that localised explosions in the populations of *Anoploganthus* spp. were consistently associated with severe damage to *E. scoparia*, an introduced species in the homestead garden.

The unbalanced nature of the data, e.g. that some species (*E. bridgesiana* and *E. microcarpa*) did not occur on all soil landscapes, and that species composition at each roadside v. paddock 'pair' was not always the same (Table 2) presented considerable difficulty for analysis and interpretation. Further, assumptions made at the time the survey was designed in 1990 were subsequently considered invalid: e.g. it was assumed that: (1) paddock sites were likely to be more fertile (e.g. due to stocking and applications of fertiliser) than those on roadsides, (2) that trees with juvenile leaves were juveniles, i.e. young, (3) that sites with an exotic-dominated groundstorey were more

fertile than those where natives dominated. As broad generalisations they may be correct but observations indicated that they were not consistent at the sites surveyed. Although tests for significant associations between the degree of leaf damage and some of the site variables could not be carried out, it does not rule them out as potential explanatory variables. However, the survey results suggest that generalisations such as

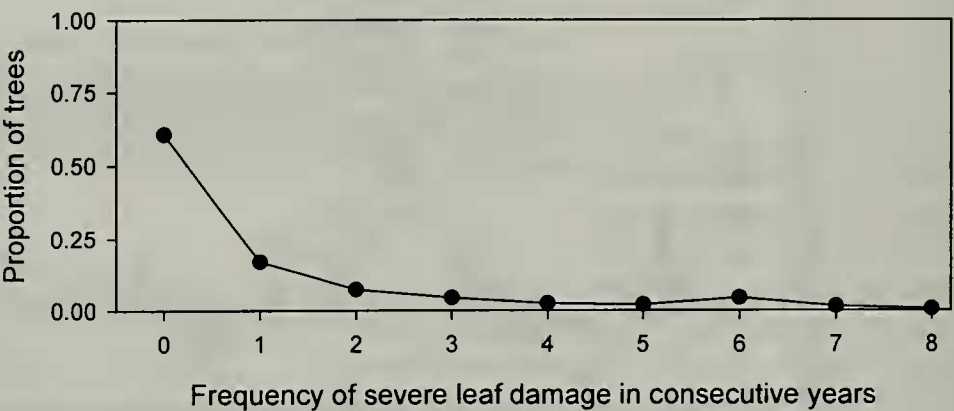


Figure 5. Proportion of trees (n = 206) that experienced varying frequencies (potential maximum = 13) of severe leaf damage (≥40 % of leaves damaged) by insects in consecutive years.

'paddock trees are more likely to suffer severe insect attack than those on roadsides' or that 'trees in intact stands, e.g. those with native groundstorey, are less likely to suffer severe insect attack', are invalid.

Monitoring of tagged trees suggested that the generalisation arising from the 'nutrient enrichment' explanation for chronic defoliation, i.e. that 'the same trees are attacked year after year', is also invalid – at least for damage by the totality of insects that feed on eucalypts. Whether it is true when Scarabeidae are abundant year after year cannot be determined

from the data available, though it too is unlikely. Scarabeidae were particularly active in the first 5 years of the observation period, yet very few trees suffered severe leaf damage in consecutive years on four or more occasions (Fig. 5). A relatively small number of trees suffered severe leaf damage in consecutive years suggesting that some trees were particularly susceptible to insect damage; though it was possible that some (unhealthy?) trees did not produce frequent flushes of new leaves and that the same leaves were observed in consecutive years. Even so, 61 % of the trees never experienced severe damage in consecutive years and of these, some were never severely damaged during the 15 years of observation.

In the case of leaf damage to the two most common species, *E. albens* and *E. melliodora*, a significant interaction was detected between time and the soil landscape in which the trees occurred. Whether this can be attributed to differing habitat qualities (e.g. 'fertility') for build-up of insect populations in average seasons (but of less relevance when insects are more mobile in times of high abundance) is conjectural. Of the three landscapes, soils in Black Rock were the least fertile (Table 1) and average levels of leaf damage were generally lower on this soil landscape except during the high damage years of 1990 and 1994 (Figs. 4c, d).

Considering the large number of insect species that feed on eucalypts (e.g. Landsberg and Cork 1997) and the effects of seasonal conditions on their abundance and on the insects and parasitoids that feed on them (Heatwole and Lowman 1986), it was surprising that correlations between leaf damage and rainfall across the 15 years of survey, or even during 1996–2004 (when Scarabeidae were uncommon), were evident at all. That the two correlations were negative ($r = -0.76$ for the three-year Foley's index for warm season rainfall and leaf damage 4 years later; and $r = -0.86$ during 1996–2004 for calendar year rainfall and leaf damage the following autumn) is difficult to explain. A correlation between rainfall and insect abundance some years later would be expected for Scarabeidae, which have long life cycles, but not for those with short life cycles such as Psyllidae. Hence, unless one or other type of insect was responsible for the fluctuating levels of leaf damage over time, correlations between leaf damage and rainfall would not be expected. Since field studies cannot afford the benefits of a fully controlled laboratory study, these correlations may be indicative of indirect associations with other non-measured variables. Perhaps the correlations should be ignored and other aspects of the rainfall record examined. For example, it was assumed at the time that the decline

in the abundance of Scarabeidae after 1994 was due to drought, especially below-average cool season rainfall, in 1994 and 1995 (Fig. 3).

CONCLUSIONS

Monitoring of insect damage to eucalypt leaves over 15 years indicated significant change over time with high damage levels evident in autumn 1990 and 1994. Though similarly high levels of damage were recorded in particular situations at other times (e.g. *E. albens* trees in the Manildra soil landscape in 2004), overall background levels of proportions of leaves damaged fluctuated between 10 and 25 %. At the commencement of the monitoring period, Scarabeidae were expected to be an on-going cause of leaf damage but this did not eventuate and damage attributed to them declined from 1994 to relatively low levels. This was possibly in response to a prolonged deficit in warm season rainfall up to 4 years earlier, though the 1994–95 drought could not be ruled out. Damage by other leaf-feeding insects, including Psyllidae, was evident throughout and they were the main cause of damage, which was generally low but high in some species and/or situations, after about 1994.

Clear relationships between leaf damage and site factors could not be determined but the results provided little support for generalisations such as 'trees in grazed paddocks suffer more insect damage than those on roadsides' or that 'trees in disturbed communities suffer more damage than those in 'intact' communities'. Relative damage to individual species changed over time but during the period when Scarabeidae were abundant, damage tended to be higher on *E. blakelyi-dealbata* and *E. albens* than on the other species. Studies of tagged trees offered little support for the generalisation that once a tree suffers severe damage it is likely to do so in consecutive years. Though this occurred to a low number of trees, many were not severely damaged at all or only occasionally.

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